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ARTICLE

Activation characteristics due to beam loss and energy dependency of its criteria for 100 MeV proton linac

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Beam loss criterion such as 1 W/m for an uniformly distributed loss has been applied at high power proton or heavy ion accelerator. It has been accepted based on the exposure level due to radioactive accelerator components during a hands-on maintenance and is a very important factor in shielding analysis of such high power, high energy accelerators. Well-developed Monte Carlo codes and inventory codes, which have been used for an activity calculation, were confirmed by benchmarking of published experimental data. The modular style method (PHITS+DChain-SP) and all-in-one style method (Fluka) using Monte Carlo code were applied to verify the criterion. The beam loss at bulk target and one-point loss at beam pipe and a uniformly distributed loss were simulated. The dose distribution and the decay scheme were compared with the control level of a hands-on maintenance. It was proved that more considerations were required instead of taking 1 W/m simply as the beam loss criterion. Especially the energy dependency effect was discussed mainly.

Keywords: proton linac; beam loss criteria; activation; Monte Carlo; energy dependency

1. Introduction

The beam loss criteria have been applied at high power proton or heavy ion accelerator. The criterion such as 1 W/m for uniformly distributed loss has been accepted based on the exposure level due to radioactive components during a hand-on maintenance since 1999 [1]. It is still a very important factor in shielding analysis of such accelerators. Recently well-developed Monte Carlo codes and inventory codes can make an accurate calculation at such condition possible. Two methods of modular style and all-in-one style using Monte Carlo codes have been applied generally.

Fluka [2] was selected as an all-in-one style and PHITS+DChain-SP [3,4] was selected as a modular style, respectively. The accuracy of each method was verified by benchmarking of proton-induced activity. The activation properties induced by 100 MeV high power proton accelerator (PEFP) [5] were analyzed using Fluka. The variation of dose levels around a bulk target and a vacuum pipe were obtained for different materials, operation schemes, and beam loss patterns. The control level of hands-on maintenance at high power accelerator was discussed based on the beam energy dependency.

2. Activation benchmarking

Both methods using Monte Carlo codes to estimate the activity were reviewed and the calculation accuracy was verified by benchmarking. The well-known data published by H. Yashima, et al. was chosen for benchmarking 100 MeV and 230 MeV proton induced activation [6]. The experimental arrangement is simply composed of layered Cu blocks (10 cm x 10 cm x 5 cm (T)) and inserted foils between successive Cu blocks.

The activities at foils were calculated and compared with the experimental data using the all-in-one style and the modular style methods. Two elements (Cu-61 and Mn-56) produced in Cu foils were benchmarked. The results are shown in **Figure 1**. The depth profile depending on proton beam energy was clearly reproduced and the good agreement was confirmed.

3. Activity calculation for beam loss pattern

3.1. Simulation model

A bulk material (ϕ5 cm x 5 cm) and a vacuum pipe (ϕ5 cm x 10 m, 2 mm thickness) were selected as targets of proton beam. In the case of a beam loss at the pipe, one point loss and an uniformly distributed loss were considered. The proton energies were 20, 100, 230, and 500 MeV in order to investigate the energy dependency.

The proton irradiation profile followed the operation plan of PEFP facility of 100 MeV proton linac. For 32 weeks a year, 4 days and 9 hours operation and 2 days and 15 hours maintenance are repeated every week.

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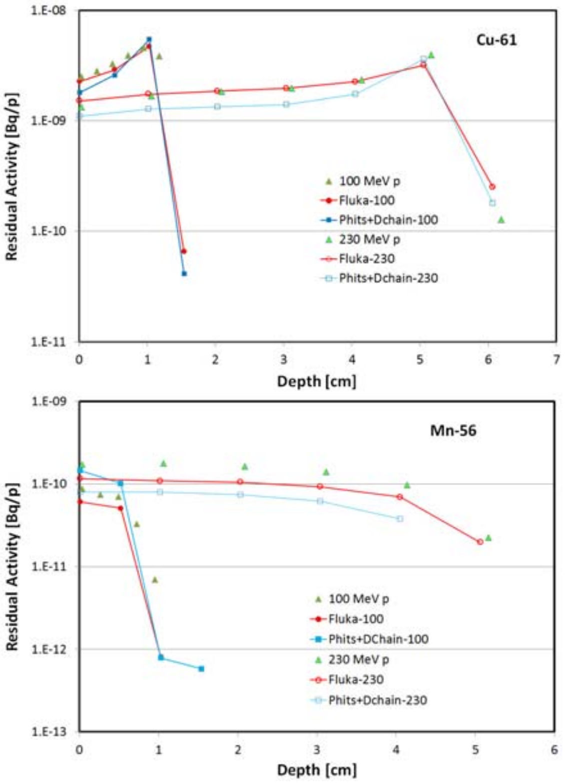

Figure 1. Benchmarking results using a module-type method (PHITS+DChain-SP) and an all-in-one method (Fluka).

■ Simulation patterns:

- Cooling time: 1 hour, 4 hour, 1 month
- Irradiation time: 1 week, 2 weeks (2cycles), 4 weeks
- Proton beam intensity of 1 W:

  For 100 MeV, 6.24E+10 protons/sec

  20 MeV, 3.12E+11 protons/sec

In this calculation, three materials, stainless steel (SUS304), Cu and Fe, were selected as a target. Those are commonly used at most of accelerator components. The activity estimation for three materials gives lots of information for the exposure expected in maintenance work. Fluka was used to estimate residual activity in targets and dose distribution around activated targets, which were compared with one another.

3.2. Dependency of target material

The dose distribution was obtained from the bulk target of stainless steel, Cu and Fe. The dose level around the stainless steel target is the highest for different energies (20, 100 MeV) and different cooling times (1 hour, 4 hours, 1 month). It is found that the dose produced at SUS304 (a vacuum pipe) is larger than one at pure Fe. Especially, it was observed clearly after a long cooling time. The dose produced at Cu (an accelerating section) was smaller than at SUS304. The produced radioisotopes and its activity in each target are shown in **Figure 2**. All figures after figure 2 were made using Flair [7].

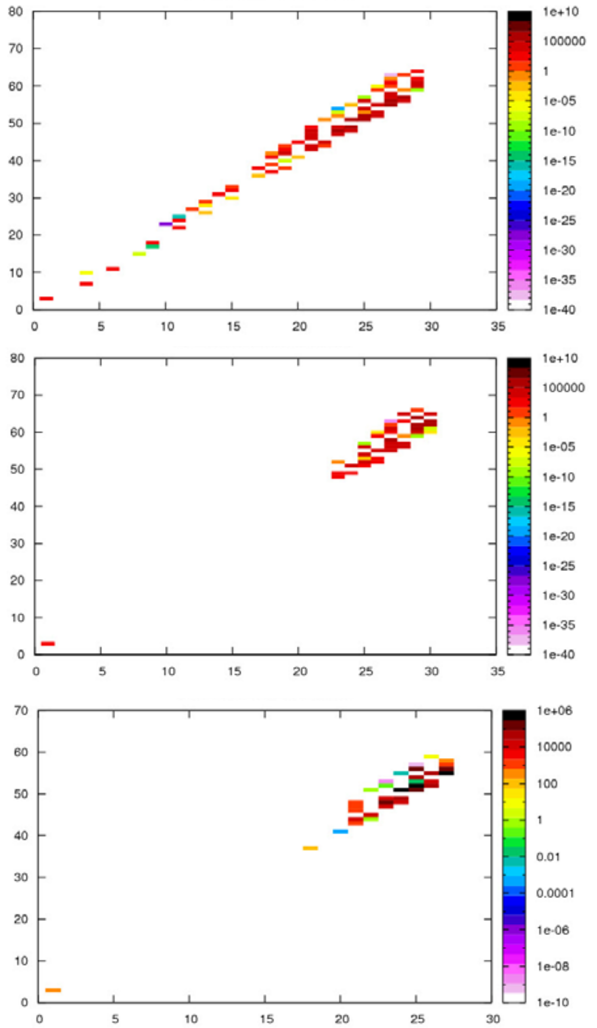

Figure 2. Distribution of isotopes produced from SUS 304 (Top), Cu (Middle), and Fe (Bottom) when 100 MeV protons strike targets. X-axis is the atomic number and Y-axis is the mass number. The unit is Bq/cm^3.

3.3. Uniformly distributed beam loss

As shown in **Figure 3**, uniformly distributed beam loss along the beam direction was assumed, but only one point was chosen at azimuthal direction in order to simulate the dose distribution and residual activities. The uniformly distributed loss at azimuthal angle can be assumed but practically such a condition is not likely. The proton beam can strike the inner surface of the beam pipe with a slant angle in practical situation. The 5 degree to surface plane was assumed as the incident angle. The dose distribution on the plane perpendicular to beam direction in **Figure 4** demonstrates the residual activity due to the beam loss pattern obviously. It is important phenomena that the opposite surface of beam loss is also highly activated and generates higher dose that the ones at 90 or 270 degree.

At the same calculation of above figure, the dose distributions along beam axis were as shown in **Figure 5**. The upper one shows the integrated dose over whole angle at azimuthal plane, while the lower one shows only dose at the range of the small arc from -30 degrees to +30 degrees. It means an angle width equivalent to the size of human body of workers who take a hands-on maintenance near a vacuum pipe. The dose integrated for the whole angle is higher than another, but the second one is more practical dose to the human worker. Therefore, the latter is used as the dose from distributed loss in the rest results of this paper.

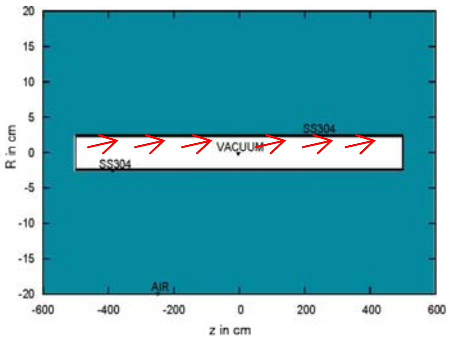

Figure 3. Simulation model of uniformly distributed beam loss. Only one azimuthal angle is selected (Arrow means the direction of incident beam. No distributed loss at the azimuthal direction).

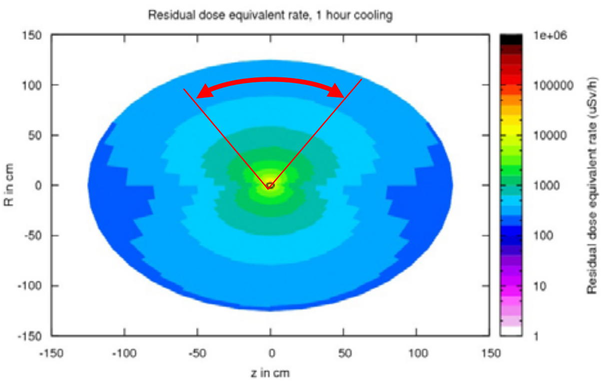

Figure 4. Dose distribution on the plane perpendicular to the beam direction. The dose from SUS304 beam pipe after 1 hour cooling time when 100 MeV proton was irradiated during 4 weeks.

3.4. Energy dependency

The thickness of a vacuum pipe or an accelerating section is variable depending on the type of accelerators and the construction reason. In this study, a 2 mm-thick SUS pipe of 5 cm outer diameter was chosen as a target.

So the dose produced by the irradiation of a proton beam can be variable depending on proton beam energies. Because the proton range is normally small, the primary proton of low energy may stop in the pipe itself. Only very high energy proton can penetrate the pipe and go out to the outer area of the vacuum pipe like an air. Four different proton energies, 20, 100, 230, and 500 MeV, were applied to check the range effect related to proton energies. The properties related to the range effect were obtained as following figures.

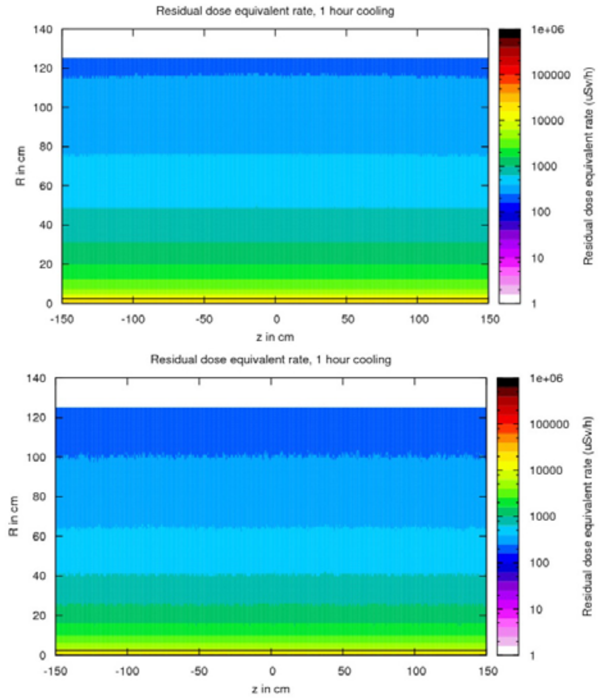

Figure 5. Dose distribution along the vacuum pipe of SUS304 irradiated by 100 MeV proton beam. Integrated for the whole azimuthal angle (Upper), Integrated for an angle width from -30 degrees to 30 degrees (Lower).

Figures 6 and **7** show the difference between 20 MeV proton beam and 100 MeV. The energy deposited by secondary particles due to 100 MeV proton beam to the air outside the vacuum pipe is higher than by one due to 20 MeV proton beam. The difference is about 2~3 orders. Another phenomenon is shown in figure7. Figure 7 is a expanded cross-sectional view to show radioactive isotopes in a vacuum pipe itself. Radioisotopes produced by 100 MeV protons are distributed at whole area of the cross-section of the vacuum pipe (2 mm region). But in the case of 20 MeV, the distribution of produced isotopes is limited only to very thin layer (0.04 mm) of the inner surface of the pipe.

The dose distributions along beam pipe were estimated at the irradiation time of 2 weeks. For two different cooling time (1 hour, 1 month), the dose distributions produced by 20, 100, 230, and 500 MeV protons were obtained. The dependency on the proton energy could be identified clearly. But after long cooling time, the difference may become smaller.

Using the obtained data from above estimation of residual activity, the dependency property of proton energy was analyzed like **Figure 8**. The dose level outside beam pipe is the highest at 100 MeV proton case for this 2 mm-thick vacuum pipe of SUS304. The dose at 20 MeV is very low and is the lowest at 500 MeV because most of protons penetrate the pipe and do not generate secondary particles to induce the activation. If the accelerating section, which is made of Cu was considered, the energy dependency may be changed a little.

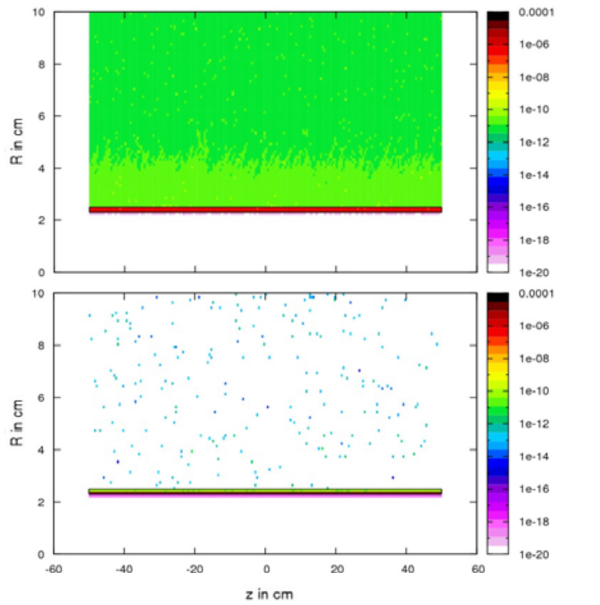

Figure 6. Distribution of deposited energies by secondary particles of 100 MeV proton (Upper) and 20 MeV proton (Lower). The unit is GeV/g.

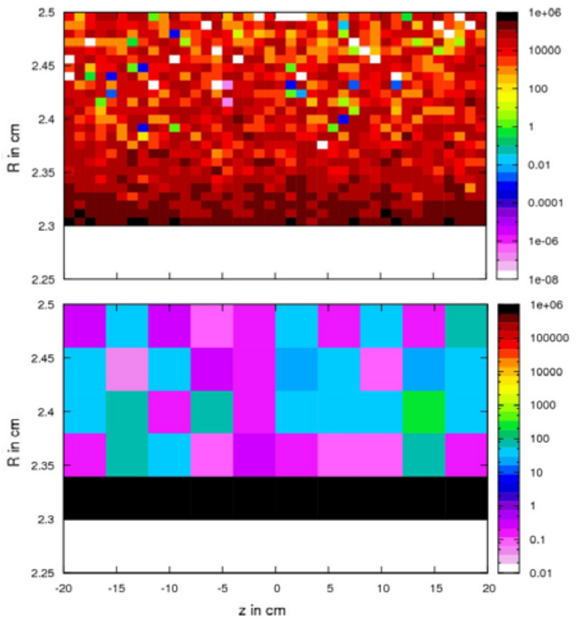

Figure 7. Distribution of radioactive isotopes produced in a vacuum pipe of SUS304 by 100 MeV proton beam (Upper) and 20 MeV proton beam (Lower). The unit is Bq/cm^3.

4. Summary and conclusion

The calculations using Fluka and PHITS+DChain-SP were proved again by the proper benchmarking. For the representative beam loss criterion of 1 W/m, the summation of each one-point loss at every 1 m distance or the uniformly distributed loss can make some discrepancy. The amount of the dose from radioactive parts outside a vacuum pipe depends on proton beam energy seriously. It is recommended to be cautious in the shielding analysis using 1 W/m criterion. So such criteria may be used for limited conditions and the proper pre-study is suggested to apply it. All-in-one style code is very useful for user to evaluate quickly the relationship between a beam loss and a dose level.

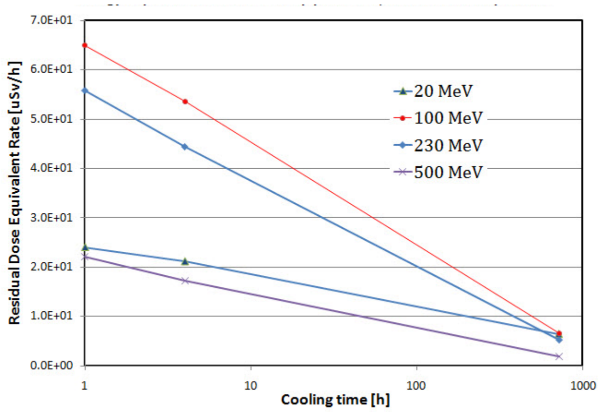

Figure 8. Energy dependency of residual doses at 30 cm from the surface of 2 mm-thick pipe after 2 weeks operation.

Acknowledgements

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